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A DEPOSITIONAL STUDY OF THE HARBOUR SEAM, SYDNEY COALFIELD, NOVA SCOTIA

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ABSTRACT

A study of the sedimentation, coal petrology and palynology has shown that: 1. Peat deposition of the main seam started in centre of basin and then migrated outward; 2. Two different phases of peat accumulation are represented by the "bright" lower part and the "dull" upper part of the seam; 3. Bright microlithotypes are higher in Lycospora(L) and dull types possess more Punctatosporites(P); 4. The L-P ratio shows that the palaeoecology was affected by two factors; 5. In one interval of the seam four environmental types can be traced laterally, in the following order: fluviatile, forested peat bog, open moor and lacustrine; 6. The occurrence of Torispora is related to the "dry" origin of one particular dull band. The density variations depend on proximity of source and most suitable medium of preservation.

Note

This paper was originally published in German in the Symposium on "Paläobotanische, kohlenpetrographische und geochemische Beiträge zur Stratigraphie und Kohlengenese", which was compiled in honour of Professor Robert Potonié of Krefeld, Germany. It was printed in volume 12 of Fortschritte in der Geologie von Rheinland und Westfalen and issued in 1964.

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INTRODUCTION

The objective of the present study was to learn more about the depositional characteristics of a Carboniferous peat bog in both its vertical sequence and lateral variations. For this purpose an attempt has been made to correlate data on the sedimentation of the Harbour coal seam, with that obtained from coal petrological and palynological examinations.

The sedimentation data were derived from detailed descriptions of cliff sections present along the shoreline and from the logs of bore-holes. The results are shown in a lithofacies map of the interval between the main Harbour seam and a seamlet designated as the Lower-Bench coal.

For the coal petrological investigations both megascopic and microscopic observations have been made. The former are portrayed in a cross-section of the seam through almost the entire extent of the Sydney coalfield. This cross-section is based on detailed megascopic examinations of polished sections representing 18 column samples. For the microscopic study the microlithotypes of one "type" column have been analyzed in order to record the vertical variation. For an insight into the lateral variations of microlithotypes, a cross-section through one selected petrographic interval of the Harbour seam is presented. These studies were carried out on polished grain mounts under reflected light with a 25X oil immersion objective.

Also discussed are some of the results obtained by a thin section examination of prominent dull bands. These bands are a characteristic feature in the Harbour seam, which permit its subdivision into time equivalent intervals.

Palynological data, based on a quantitative evaluation of the miospore genera present in the 15 subdivisions of the "type" column were used to establish the vertical changes in vegetation. The regional changes were recorded only on the same petrographic interval that was used to study the lateral microlithotype variations. This required a statistical analysis of 14 samples. A map, showing the regional distribution of the genus Torispora in one particular layer of the Harbour seam, is also presented. This distribution is expressed as spore density per square mm., and was obtained from microscopic examinations of polished and thin sections.

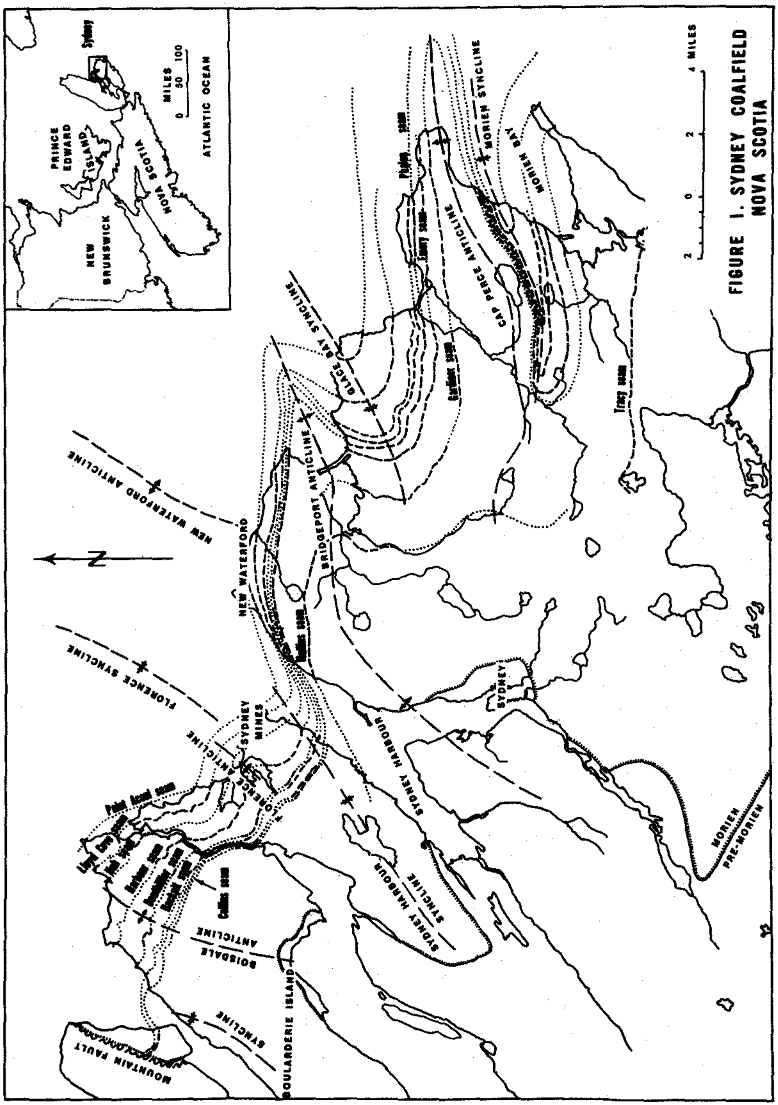

FIGURE 1. SYDNEY COALFIELD NOVA SCOTIA

As the Harbour seam forms an integral part of the Sydney coalfield, and as such has been affected by its general geological conditions, a brief outline of this field is presented in the following section.

LOCATION AND GEOLOGICAL OUTLINE OF SYDNEY COALFIELD

The Sydney coalfield, situated in the northeastern part of Cape Breton Island in the Province of Nova Scotia, occupies a narrow fringe of lowland coast along the Atlantic Ocean (see Fig. 1). When measured in a straight east-southeasterly direction the field is 31 miles long, and east of Sydney reaches a width of 19 miles in the land area. The seaward extension of the coalfield is not known, but according to Bell (1938) may exceed 30 miles.

All coal bearing rocks in the area belong to the Pennsylvanian Morien series, which on the basis of the megaflora and spore florule (Bell, 1938; Hacquebard et al., 1960) has been assigned a Westphalian C and D age. The series reached its maximum thickness of around 6,450 feet in the Glace Bay and Port Morien districts, and is transgressive towards the northwest, where it overlaps on older strata.

There are twelve mineable coal seams in the upper half of the Morien series, all of which are remarkably similar in rank, notwithstanding their stratigraphic separation. According to the A.S.T.M. system, all Sydney coals are classed as high volatile "A" bituminous. In volatile matter content, on the dry mineral matter-free basis, the seams vary only between 36 and 40 per cent.

The tectonic development of the Sydney coalfield has been comparatively gentle and serious structural difficulties have not been encountered in the mine workings. In general, gentle folding and only minor thrust faulting is represented. The folds fan out seaward and, with few exceptions, trend in a northeasterly to easterly direction, with a gentle seaward plunge of their axes. The prevailing dips throughout the coalfield are from 4 to 15 degrees. Although the main orogenetic movement occurred after the deposition of the Morien series (during the Appalachian revolution) Haites (1951) was able to show that the present fold pattern was initiated by warping during deposition.

Coal has been exploited from the Sydney field since 1720 when it was first dug out from the sea cliffs by the French in the Port Morien district during the construction of the fortress of Louisburg. Systematic mining has been carried out for more than a century, and the bulk of the production has been obtained in the submarine area from two major coal seams, namely the Harbour and Phalen seams.

For the present study the Harbour seam was selected, because it maintains a mineable thickness over a greater areal extent than any other seam. Consequently a greater number of mines have penetrated the submarine area of this seam. This afforded excellent opportunities to measure seam sections and collect column samples for petrographic and palynological studies over a large area. A wealth of information is available on the coal itself, most of which can be found in the detailed report on the Harbour seam by Haites (1950). Information on the sediments between the coal seams is generally very restricted, particularly in the submarine area. This is due to the system of mining, in which each colliery normally extracts only one seam. This seam is entered from the surface outcrop by a slope, or a shallow vertical shaft. As a result, there are very few interseam tunnels, and bore-holes occur only in those submarine areas where exploration from one seam to another by underground drilling appeared to be warranted. To some extent the lack of interseam data in the underground workings is offset by the excellent exposures in the sea cliffs along the entire shoreline of the Sydney coalfield.

FLOOD-PLAIN SEDIMENTATION AND PEAT ACCUMULATION

The Sydney field belongs to the limnic basins of coal deposition, in which marine incursions have not been recorded. The deposition of the coal seams and accompanying fluvial and fluviolacustrine sediments took place in a valley-flat or flood-plain environment (Hayes and Bell, 1923; Haites, 1951). Meandering rivers carried the erosion products of a hinterland into a slowly subsiding basin. Bell (1938) has pointed out that the pre-Carboniferous Cape Breton Highlands, situated to the northwest of the coalfield likely represent the old "positive" area during the deposition of the Morien series. The supply of sediments from this hinterland was apparently always sufficient to maintain the level of the flood-plain above sea-level.

The distribution and accumulation of the clastic sediments was controlled entirely by the river courses and their transporting power. The coarser sediments of the bed-load were laid down in the river channel or on its border as natural levees. The fine-grained suspended load was carried into the interdistributary areas by overbank flood-waters during periods of excessive water supply. However, no sharp boundary exists between bed-load and suspended load, and consequently many transitions between sandstones, siltstones and shale occur. Fisk (1960), in a most interesting paper on recent Mississippi deltaic deposits, has shown that vegetation and peat formation are related to the distribution and nature of the clastic sediments. An important factor in this relationship is the variation in relief due to differential compaction. The effect of compaction by itself can provide areas of poor drainage and subsidence necessary for the accumulation of thick peat

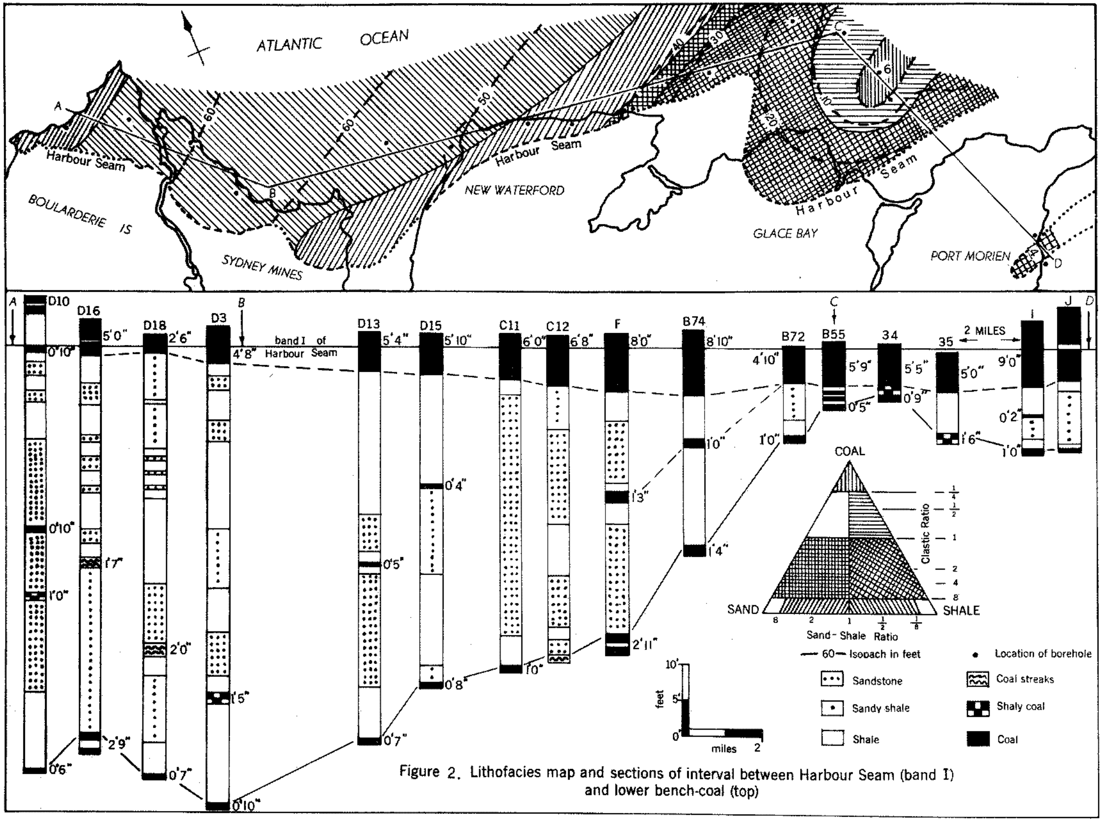

Figure 2. Lithofacies map and sections of interval between Harbour Seam (band I) and lower bench-coal (top)

deposits. The most favourable areas for this, according to Fisk, are in the interdistributary troughs and levee-flank depressions along the active and abandoned river channels. These areas would be those underlain by fine clastic sediments.

From the preceding discussion it is clear that the nature of the sediments and the topography of the surface immediately underlying a peat bog, or a coal seam, can provide much valuable information on its mode of deposition. For this reason a study has been made of a sequence of time-equivalent sediments associated with the Harbour seam. The interval considered lies between the distinctive dull band I of the Harbour seam and the top of the Lower Bench coal. Both marker horizons could be traced through the entire coalfield, and are regarded as reliable time lines. The sediments present in this time-rock unit are shown in the stratigraphic sections of Figure 2. They are plotted along the line A, B, C, D, which runs from Boularderie Island in the west to Port Morien in the east. From these sections it is at once apparent that the clastic parting between the Lower Bench coal and the Harbour seam increases in thickness both to the west and to the south of sample 34. This means that after the deposition of the Lower Bench coal there occurred a large influx of clastic material, particularly in the western part of the field where it reached its maximum thickness of 60 feet, in bore-hole D-3. During this time the formation of peat came largely to a halt, with the exception of a few isolated areas, now represented by thin coal layers shown in some of the bore-hole sections.

Together with an increase in thickness of the clastic parting, changes in its lithology are also noticeable. An areal expression of these changes is presented in the lithofacies map of Figure 2. This map is constructed in accordance with the concept of end-member ratios as proposed by Krumbein and Sloss (1951). The three end-members present here are coal (nonclastic), sandstone and shale (clastics). The clastic ratio is obtained by dividing the total aggregate thickness of the clastics present in the section by the sum total of the nonclastics. The sand-shale ratio is the ratio of sandstone plus conglomerate to shale in the section, regardless of the amount of nonclastics. The ratios are plotted in the ternary diagram shown in the legend. Following Krumbein and Sloss (1951) the triangle has been subdivided into nine areas, each representing a different type of lithology. This lithology, by its characteristic shading as shown in the legend-triangle, is plotted on the lithofacies map.

Although based on an inadequate number of control points in most of the submarine area, the map indicates that the gross lithology of the interval is not randomly distributed. Two areas relatively high in sand are represented, namely on the west side of Boularderie Island and across the New Waterford district extending into the Sydney Mines region. These two areas are considered to have been the sites of distributary channels of the river responsible for the deposition of the clastic detritus between the main Harbour seam and the Lower Bench coal. The region between these two channels may be regarded as an interdistributary trough in which the finer clastic material was laid down, possibly during periods of flooding.

The Glace Bay district was least affected by the river sedimentation, which in part may be due to the protection afforded by a natural levee that bordered the New Waterford distributary channel on the southeast side. Quiet, subbasin type of sedimentation with a relatively slow rate of subsidence appears to be indicated for this region. This is concluded from the dominance of fine clastic shale and nonclastic coal, and the approximately concentric ovate parallelism of the isopachs and facies lines (Krumbein, 1952).

A comparison between the change in thickness of the clastic parting and the height of Harbour coal below the datum line of band I in the sections of Figure 2 reveals an interesting relationship. The increase in thickness of the parting to the west is accompanied by a gradual decrease in height of coal. This phenomenon is related to the palaeotopography that existed during the early stages of the Harbour peat accumulation. Higher ground was present in the western region due to the great influx of clastic materials. Differential compaction caused by differences in sedimentation produced a basin-type area during the formation of peat. In this area active peat accumulation first started in the centre, at Glace Bay, while clastic sediments were still being laid down in the western part. As time progressed, the peat forming vegetation migrated outward from the trough or subbasin across the postulated levee and distributary channel of New Waterford, across the Sydney Mines interdistributary trough and finally covering the Boularderie river channel. It was only after this point was reached that simultaneous peat deposition occurred over the entire areal extent of the Harbour seam.

This aforementioned sequence of events is based on a detailed time correlation of the petrographic intervals recognized in numerous column samples of the Harbour seam, of which eighteen are shown in Figure 3. This correlation will be discussed in the next section. The depositional history here described is in close agreement with the one illustrated by Fisk on the progressive stages of peat accumulation in the Mississippi deltaic plain (1960, p. 194, Fig. 5). It is not entirely in accord with the views held by Wanless (1956), who assumed that throughout the depositional basins active peat accumulation took place at the same time.

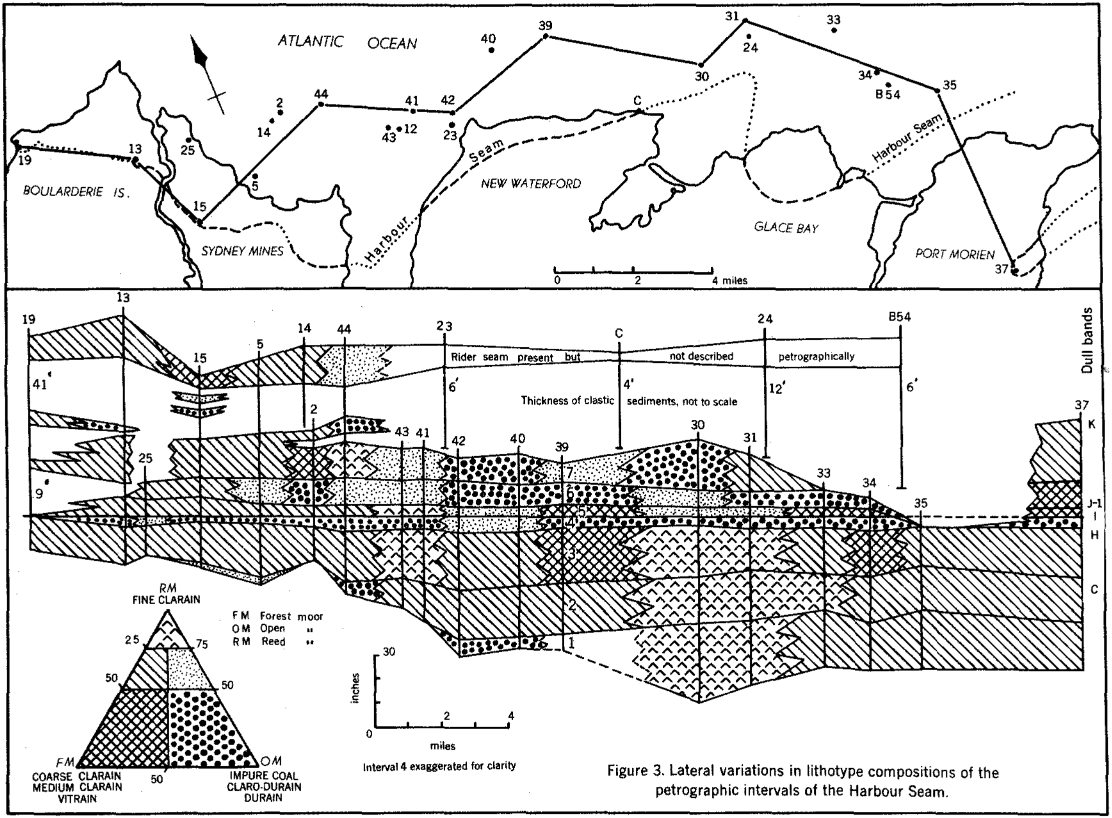

Figure 3. Lateral variations in lithotype compositions of the petrographic intervals of the Harbour Seam.

FACIES CHANGES IN THE HARBOUR COAL SEAM AS DEDUCED FROM LATERAL LITHOTYPE VARIATIONS

Figure 3 represents a cross-section through the Harbour seam from the west shore of Boularderie Island to Port Morien. This section is based on a megascopic study of polished sections obtained from eighteen column samples. The seam profile at each sample location has been subdivided into petrographic intervals, which in the authors' opinion represent time-rock units. They are bounded at top and bottom by selected dull layers (see Figure 4), which possess widespread continuity and a characteristic microscopic composition. These selected dull bands have been studied previously by Cameron (1961) by means of thin sections.

In each petrographic interval the aggregate thickness of individual lithotypes is expressed as a percentage of the total thickness of the interval. These percentages are plotted in a ternary "facies" diagram, which is shown in the legend of Figure 3. The vertices of this triangle are occupied by those lithotypes or combinations of lithotypes that represent specific environments in the peat bog. The fusain was not placed at any particular vertex, but instead was grouped with the lithotypes, e.g. fine clarain or durain, with which it was associated in the sample.

Following the procedure of von Karmasin (1952) three types of environment within the swamp are considered here, namely the forested moor (FM), the reed moor (RM) and the open moor (OM). Based in part on studies of Tertiary brown coals by Teichmüller (1950, 1952) and by Teichmüller and Thomson (1958), the forested moor is regarded as the environment for the deposition of vitrain and clarain; the open moor for the largely subaquatic deposits like cannel, boghead and certain types of spore-rich durain; and the reed moor as a transitional area for the deposition of cuticle clarain and clarain with distinct microbanding (fine clarain).[1]

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[1] Clarain (as defined in the 1957 Glossary) is here subdivided according to the thickness of the vitrinitic bands.

Fine clarain	> 50%	of bands	<	1 mm	thick
Medium	"	"	"	1 - 2 mm	"
Coarse	"	"	"	2 - 3 mm	"

The three types mentioned form the end-members of the "facies" triangle in much the same manner as coal, sand and shale in the lithofacies triangle of Krumbein and Sloss (1951). The subdivision here into five parts was accomplished by blocking off areas that contain the largest number of nearly similar lithotype compositions. The facies changes of the Harbour seam are plotted in the cross-section of Figure 3 by means of these five units.

From the section it can be noted that there were two distinctly different phases during the development of the Harbour peat bog. Both phases can be observed not only vertically in one sample, but also regionally between different samples. With the deposition of interval 4 a major change affected the peat accumulation over the entire area. The older phase, comprising intervals 1, 2 and 3, is characterized by a great predominance of the bright lithotypes (vitrain and clarain). The prevailing environment during this time was intermediate between FM and RM, which locally changed into a true forested bog or a true reed moor. The latter, however, was a permanent feature on the northwest side of the Glace Bay subbasin (samples 30, 31 and 33 in part). This area is near the postulated natural levee of the New Waterford distributary channel (see Figure 2). This proximity may have produced an environment with a groundwater level in the peat bog favourable for a reed moor facies. Interesting in this respect is also that the total thickness of the Harbour seam reached its maximum height of 9 feet in sample 30. According to Fisk (1960), the thickest peat deposits in the Mississippi deltaic plain occur in the levee-flank depressions along the active and abandoned river channels.

From previous microscopic and chemical investigations on the Harbour seam by Hacquebard (1960) and Hacquebard and Tibbetts (1960), it is known that in the area around sample 31 in Dominion No. 26 colliery exceptionally clean and low-sulphur coal was deposited. The lower three intervals of sample 31, when considered as a whole, contain 2.5 per cent ash and 0.9 per cent sulphur. On both sides of this area these figures increase, namely to 5.0 per cent ash and 2.0 per cent sulphur in the New Waterford and Sydney Mines districts, and 6.5 per cent ash and 3.8 per cent sulphur in the centre of the Glace Bay district. This change in ash and sulphur content is not accompanied by any observable difference in microscopic composition. Over the entire field the aggregate amount of vitrite plus clarite in intervals 1 to 3 varies only between 75 and 85 per cent. Duroclarite, always of the granular-micrinite variety, is present between 8 and 12 per cent. As regards the macerals, vitrinite lies between 71 and 78 per cent, exinite between 7 and 11 per cent, and inertinite between 11 and 16 per cent.

The microscopic data suggest that the environment which produced the lower three intervals would in general be favourable for the formation of syngenetic pyrite, the major sulphur bearer in the Sydney coals.

However, this is not the case in the vicinity of sample 31. The mode of peat accumulation as expressed in its texture or type of layering, may be responsible for this. In this connection it is worthy of note that in the restricted area of 31 the fine clarain or reed moor facies dominates the lower three intervals. The particular environment responsible for this variety of coal was apparently not an environment suitable for sulphur precipitation in the form of pyrite. It also was a region with little influx of water containing suspended clay particles, in view of the low ash content observed in the coal.

The first phase of Harbour peat deposition took place in a mixed forested and reed covered swamp environment. This environment lasted until the deposition of interval 4, although it was at times interrupted by short periods of open moor conditions, during which thin dull bands were formed. The most notable of these is band C. This band represents a short time of general flooding over the entire peat bog that existed up to that time. It represents the upper boundary of interval 2 and is characterized by a high ash content that averages 26.4 per cent. It is remarkable that notwithstanding the widespread distribution of band C and the OM facies represented in it, this facies was of such restricted duration. It had no or little effect on the overall environment of interval 3, which continued to be of the same general character as intervals 1 and 2.

The first phase of Harbour peat accumulation, which at sample 30 lasted at least 1,800 years[1] was terminated with the formation of band H. The second phase, comprising intervals 4 - 7 and lasting at least 1,000 years (at sample 37), was one during which the OM and intermediate RM-OM environments repeatedly encompassed large areas of the swamp. After the deposition of band H, which due to its high content of brown vitrinite and (massive) micrinite (Cameron, 1961, p. 145) likely signifies a period of desiccation, there probably occurred a general rise in the groundwater level over the entire area. This increase was general and intermittent. It first expressed itself during the deposition of band I, which, on account of its high percentage in both exinite and brown vitrinite, was likely subjected to rather rapid water level fluctuations. As the ash content of band I is persistently low (averaging 4.4 per cent) no river flooding of the peat bog, but a general rising and falling of the groundwater level is envisaged. This occurred not only during band I, but also during the following intervals, particularly during the formation of interval 6. A characteristic feature of this interval is the rapid alternation between thin durite and clarite bands,

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[1] Ashley (1907) calculated the (minimum) time necessary for the accumulation of 1 foot of bituminous coal at 300 years.

at least in the central part of the coalfield. On its flanks, in the areas of Boularderie Island and Glace Bay much more severe water level changes were encountered.

On the west side of Boularderie Island river sedimentation interrupted the peat growth during intervals 5 and 6, with the deposition of a 9-foot thick clastic parting (in sample 19). This parting can be traced as far east as sample 15, where it is represented by a 1/2-inch-thick band of carbargilite that lies at the top of interval 6. There, as well as in sample 13, this river only affected the peat bog during interval 6. Next, in time, it meandered back to 19 where it laid down 15 inches of shale during interval 7, and still later 2 inches of shale near the top of sample 13. In other words, a river climbed the section during the upper phase of peat deposition in the extreme western part of the field. It eventually terminated the Harbour peat growth completely by flooding the entire region and depositing the clastic sediments of the roof rock. When this happened, the main channel of this river was located on the east side of Boularderie Island, where it eroded existing peat to different levels (at location of sample 25), and even removed it entirely in the actual channel. The history of this "wash-out" and the projected meandering course of the river can be found in the reports of Haites (1950, 1951). A sandstone roof overlying the Harbour seam in this part of the field is considered one of the diagnostic features associated with the wash-out.

In the Glace Bay subbasin the upper part of the seam is also displaced by clastic sediments, but here only fine clastics (mud-cracked shale) and even non-clastic fresh-water limestone is represented (Haites, 1950). Accordingly, not fluvial but more likely lacustrine sedimentation terminated the Harbour peat accumulation in this area. This sedimentation was largely contemporaneous with the deposition of the upper four intervals.

From the preceding discussion it is apparent that essentially five different environments affected the peat deposition of the Harbour seam, which produced five different facies. In the lower phase (intervals 1 - 3) the facies represented by the reed moor and the partially forested moor greatly predominate. In the upper phase, the open moor type occupied large areas in the centre, which were bounded on either side by partially forested regions and by fluvial and lacustrine environments.

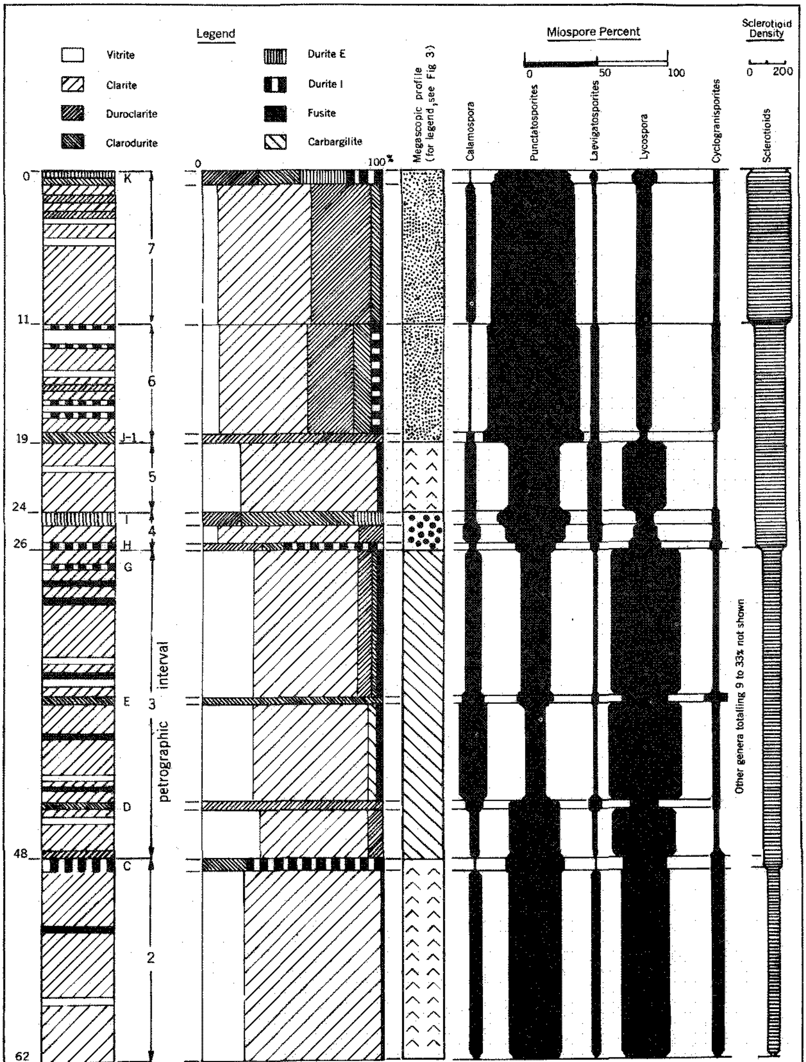

Figure 4. Petrography and palynology of a typical column sample of the Harbour Seam (IV-12)

VERTICAL FACIES CHANGES AND MIOSPORE SUCCESSIONS IN A TYPICAL COLUMN SAMPLE OF THE HARBOUR SEAM

The column sample discussed here was collected in the Princess colliery of the Sydney Mines district at location 12 in Figure 3. The seam is slightly over 5 feet thick, and contains all but one of the seven petrographic intervals. The oldest interval is not present, because during that time there was no peat accumulation as yet in this area.

The petrography shown in Figure 4 was obtained from a microscopic and megascopic study of 37 polished sections, which together represent the full thickness of the seam. The microscopic results, in terms of microlithotypes, have been plotted in the two columns on the left, which are referred to as the coal-log and the percentage diagram. The latter shows a more refined subdivision than is normally presented, when only entire petrographic intervals are considered (Hacquebard, 1952). Here the seven characteristic dull bands, previously examined by Cameron (1961) are shown separately. These dull bands, along with the intervening bright layers, represent the fifteen subdivisions of which the microlithotype compositions are illustrated. The percentage diagram of Figure 4 is typical of the Harbour seam. It differs from the other coal seams in the Sydney field, and can be used for correlation and identification purposes.

The fifteen vertical alternations in composition are caused by changes within the broad facies that are represented by the six petrographic intervals. The latter can be recognized by means of a megascopic inspection alone, and their facies character is illustrated in the third column in the same manner as was done in Figure 3.

Exclusive of the dull bands, which will be discussed later, the microscopic composition of the facies represented by the six intervals may be summarized as follows:

Interval 2. A reed moor facies, represented by a predominance of fine clarain. The dominant microlithotypes are clarite and vitrite. A very subordinate amount of fusite and duroclarite is present. Clarite that is largely free or almost free of (granular) micrinite occurs abundantly. Its main components are cuticles and miospores, which possess a well preserved appearance. Total maceral composition (exclusive of band C) is as follows: vitrinite 72 per cent, exinite 13 per cent and inertinite 15 per cent. The inorganic microscopic constituents observed are some finely disseminated pyrite and a few very small siderite concretions. The ash content is 2.15 per cent, the sulphur 0.86 per cent, and the volatile matter (dry, mineral-matter free) 38 per cent.

Interval 3. A mixed forested and reed moor facies, represented by alternating bands of fine, medium and coarse clarain, as well as vitrain. The dominant microlithotypes are clarite and vitrite. A fair amount of duroclarite and fusite is present. Both clarite and duroclarite are characterized by granular micrinite. Well preserved miospores, cuticles and a few megaspores are present. The total maceral composition (including the dull bands) is as follows: vitrinite 72 per cent, exinite 9 per cent and inertinite 19 per cent. Very little syngenetic pyrite and a few thin layers with siderite concretions were noted. Ash is equal to 2.00 per cent, sulphur to 0.53 per cent, and volatile matter to 37 per cent.

Interval 4. An open moor facies, represented by the two durain bands H and I, and intervening fine clarain. The characteristic microlithotypes are durite E, durite I, clarodurite and duroclarite. These have variable amounts of micrinite, and both the granular and massive types are present. The microscopic differences between bands H and I will be discussed in a later section. In the dull bands the sporinite occurs in two forms, namely as a highly corroded matted mass of exinite, in which vague outlines of original spores can only be detected at high magnification, and as ordinary well preserved spores. The latter are often embedded in the former and may include *Torispora*. Megaspores are also present, but not abundant. In the overall maceral composition of interval 4, vitrinite is present by 56 per cent, exinite by 22 per cent and inertinite by 22 per cent. A very minor amount of pyrite was observed only in the vitrite and clarite situated between bands H and I. Ash is 2.2 per cent, sulphur 0.54 per cent, and volatile matter 44 per cent.

Interval 5. A reed moor facies, represented almost entirely by fine clarain. The microscopic composition is very similar to the one reported for interval 2. Here the cuticles seem to dominate the clarite composition even more, and in several narrow bands a true cuticle coal is represented. Total vitrinite is 82 per cent, exinite 8 per cent and inertinite 10 per cent. From the proximate chemical analysis the following data were obtained: ash 4.62 per cent, sulphur 0.49 per cent and volatile matter 42 per cent.

Interval 6. A mixed open moor and reed moor facies, represented by alternating thin bands of fine clarain, clarodurain and durain. The prevailing microlithotypes are clarite, duroclarite, clarodurite and durite I. In these types the granular micrinite predominates. It occurs in association with abundant, well preserved miospores, megaspores (in certain restricted layers) and sclerotioids. Total vitrinite is 60 per cent, exinite 12 per cent and inertinite 28 per cent. Finely disseminated pyrite and small siderite concretions occur throughout this interval. Ash is 4.18 per cent, sulphur 1.37 per cent and volatile matter 38 per cent.

Interval 7. A mixed reed moor and open moor facies, comparable to interval 6, but with the accent on the first rather than on the second type of environment. It is represented by the same alternation of lithotypes as in 6, only the layers with fine clarain are thicker. Clarite and duroclarite with granular micrinite are predominant. Total vitrinite is 66 per cent, exinite 13 per cent, and inertinite 21 per cent. Miospores, cuticles and sclerotioids are abundant, and occur in a well preserved condition. Some finely divided pyrite is present and becomes very high in band K. A few siderite concretions occur near the bottom of this interval. A proximate analysis, exclusive of band K, shows 2.29 per cent for ash, 0.68 per cent for sulphur and 37 per cent for volatile matter. The ash and sulphur contents of band K are respectively 22.52 per cent and 3.07 per cent.

As part of the petrographic study a simple quantitative evaluation of the sclerotioids present in the Harbour seam has also been made. The telescopic pattern shown in the distribution bar at the extreme right of Figure 4 indicates a gradual increase in density from 64 in interval 2 to 236 in interval 7. It is interesting to note that this increase roughly parallels that of the total amount of inertinite, which varies between 15 and 22 per cent. As nowhere in the Harbour seam the amount of sclerotinite exceeds a few per cent, and is therefore barely responsible for the fluctuations in total inertinite, the relationship may be genetic, rather than quantitative. Apparently, the conditions which favoured the origin of inertinite in general, were also favourable for the development of the sclerotioids. An OM environment, with possible subaquatic origin, seems to have been the most conducive to the formation of these entities. Following a previous study by Hacquebard (1951), the name sclerotioid is used for all bodies that resemble or possibly represent a compact mass of fungal hyphae in a dormant state (i.e. a sclerotium). The sclerotioids therefore include the structureless, carved or vesicled round bodies, which according to Kosanke and Harrison (1957) represent opaque resin rodlets.

The palynological data presented in this paper are based on a statistical study of miospore genera, which have been classified according to the system of Potonié and Kremp (1955-56). Each spore assemblage shown, was obtained from a count of two hundred specimens. The entire spore population observed in the Harbour seam consists of fifty-one genera, which are listed in the *Ptychocarpus unitus* zone of the Morien Group in Figure 4 of the publication by Barss et al.(1963). It includes such characteristic genera as e.g. *Foveolatisporites*, *Verrucososporites*, *Torispora*, *Murospora*, *Schopfites*, *Mooreisporites* and *Densosporites*. As was mentioned previously, a Westphalian D age for the Harbour seam is indicated by both the spore florule and the megaflora.

In Figure 4 the vertical distribution patterns of five genera through fifteen subdivisions are presented. The other genera all occurred by less than 6 per cent of the assemblage, except Torispora and Granulatisporites. Only in two instances did these two genera surpass the 6 per cent margin. In band D Granulatisporites reached 10 per cent, and in band H Torispora is present by 12 per cent. Of the five genera that have been plotted, Punctatosporites and Lycospora together, always total more than one half of the assemblage. These totals vary between 51 per cent in band H to 77 per cent in J-1. Between these two genera, moreover, there exists an inverse relationship. An increase in Punctatosporites is accompanied by a decrease in Lycospora, and vice versa. A similar relationship, but less pronounced, exists between Calamospora and Laevigatosporites, and a higher percentage of the former is accompanied by a greater abundance in Lycospora. As regards the genera Laevigatosporites and Cyclogranisporites, no such correlations are apparent.

From the palaeobotanical affinities of certain Carboniferous miospores it is possible to obtain a picture of the type of vegetation. A dominance of Lycospora probably indicates a forested area composed largely of arborescent Lycopods, such as e.g. Lepidodendron. The affinities of Punctatosporites favour a more herbaceous type of flora (Smith, 1962). The ecological conditions in recent peat swamps control both the type of peat formation and its supporting vegetation. That this was also the case in the Carboniferous peat bogs can be seen in Figure 4. Here it is illustrated that there exists a correlation between the vegetation, as expressed by the miospores, and the environment of peat deposition, as interpreted from the petrographic composition.

The reed moor environment of intervals 2 and 5 probably supported a mixed vegetation composed of herbaceous and arborescent plants. In both intervals Punctatosporites and Lycospora are about equally represented, namely by 35 and 33 per cent, respectively. Interval 3, although also a very bright coal, but one that originated in the more forested RM-FM environment, likely carried a more arborescent vegetation. There the genus Lycospora is present by about 50 per cent, and Punctatosporites by less than 20 per cent. It is interesting to note that in interval 3 the genus Calamospora reached its acme of 16 per cent (between bands D and E). This may indicate a relationship of Calamospora to the partially forested bog.

The open moor environment of interval 4 started with the "dry" conditions of band H. During and immediately following this time the genus Torispora reached its maximum of 12 per cent. In all other subdivisions it only varied between 1 and 3 per cent. As Torispora is probably closely related to xerophytic or drought-resistant Sphenopterids (seed ferns) (Neavel and Guennel, 1960), its relatively abundant occurrence in association with band H seems to confirm the desiccated origin of this band.

When interval 4 is considered as a whole, it becomes apparent that for the first time in the history of the peat bog, a herbaceous vegetation becomes the dominant feature. This is concluded from the increase in Punctatosporites and decrease in Lycospora as compared with intervals 2 and 3. A distinct floral change took place with the deposition of band H. This was also noted with band D, but not in band C. The latter is the high-ash band which was interpreted as the result of a rapid flooding of the peat bog, rather than a gentle rising or falling of the groundwater level as during D and H. In this connection it is worth noting that Smith (1962) also made the observation that the high-ash, fusinite enriched durain bands did not disrupt the continuity of the preceding vegetation.

The mixed reed moor and open moor environment of intervals 6 and 7 were favourable for a vegetation composed of herbaceous forms. This is concluded from the dominance of Punctatosporites, which here varied between 52 and 70 per cent. The arborescent Lycopods became greatly reduced, and accordingly only an average of 12 per cent Lycospora are present in these two intervals. Calamospora likewise diminished, namely to 5 per cent and less.

The results obtained on palyno-petrographic studies carried out on British and French Carboniferous coals by Smith (1962) and Navale (1962) differ somewhat from those reported here. This is due largely to the absence of crassidurite (Stach, 1954), and its accompanying high concentrations of Densosporites. In the Harbour seam this genus never reached more than 2 per cent. Likewise, the genus Torispora, which plays such an important part in Navale's studies, is here a subordinate component of the spore florule, with only one exception (band H). In contrast to some of the British and French coals examined, the Harbour coal is in general of a brighter variety, with the duller portions (except the thin durain bands) possessing an intermediate, rather than a durite microlithotype composition. Nonetheless, the relationship observed in the Harbour coal between the "dull" microlithotypes and Punctatosporites, and the "bright" types and Lycospora is in agreement with the results obtained by Smith.

THE PALYNO-PETROGRAPHY OF SELECTED DULL BANDS OF THE HARBOUR SEAM

The seven megascopically dull bands are marked C to K in Figure 4. The petrographic variations of these bands over most of the Sydney Mines district have been previously reported by Cameron (1961). The microscopic examinations were carried out by means of transmitted light and the results, as related to the "type" column only, together with the corresponding miospore data, are shown in Figure 5.

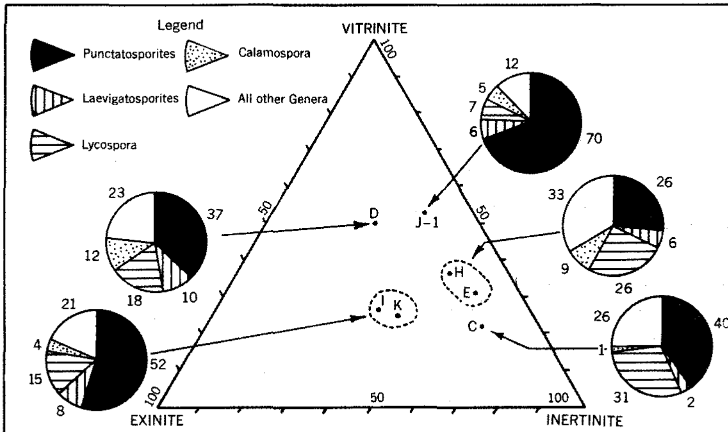

Figure 5. Maceral compositions and miospore florules of selected dull bands of one column of the Harbour Seam

The petrographic composition is expressed in terms of the group macerals, vitrinite, exinite and inertinite. Exinite includes resinous bodies as well as the remains of spores and cuticles, while inertinite includes a number of components, namely, brown vitrinite, micrinite, semi-fusinite and fusinite.

These seven bands exhibit a considerable range in their maceral composition. Two of them, bands D and J-1 are relatively high in red vitrinite, which occurs in a very finely divided state. They contain well preserved spore remains and a low content of brown vitrinite. They are thought to represent a more open moor environment, one that was perhaps characterized by the growth of herbaceous or reed-like plants.

Bands E and H are much alike in their maceral compositions. They are considered to be the products of periods of desiccation. Brown vitrinite, which is an important element in their composition, is thought to be equivalent in part to the "decay" fusinite of Teichmüller (1950) and von Karmasin (1952), and in part to massive micrinite. Additional evidence for a "dry" origin for these bands is the fact that the exinite contents are relatively low and the spores show signs of corrosion. Band C is also high in inertinite, but much of it is fusinite. This is accompanied by a high ash content (27 per cent). Accordingly, as has been mentioned previously, band C is likely the product of flooding.

Bands I and K are somewhat more difficult to characterize. They are high in exinite, much of which is in the degraded, matted condition mentioned in the preceding section. The degraded condition of the spores and the relatively high content of brown vitrinite suggest a "dryer" than normal environment of deposition. The abundance of spores, however, suggests "wet" conditions. An unstable environment with considerable fluctuations in the groundwater level seems to be indicated.

The pie diagrams shown in Figure 5 represent the miospore compositions of the seven bands. As the assemblages of I and K, and E and H, respectively, are similar, only the average is plotted. In comparing the petrography with the spore assemblages certain predictable relationships appear. Bands E and H which are attributed to "dry" conditions show the lowest content of _Punctatosporites_. On the other hand, D and J-1 are higher in _Punctatosporites_, which is to be expected if the conclusions regarding their origin are correct and if _Punctatosporites_ is indeed the spore of herbaceous plants that favour a relatively "wet" environment. Band D contains the highest percentage of _Calamospora_, which is to be expected since this genus is associated with the brighter coal in this seam. However, _Calamospora_ is low in J-1. Another anomaly is that those bands characterized by the highest amounts of opaque and semi-opaque matter, namely bands C, E and H, contain the highest percentage of _Lycospora_ while band J-1, which has a much higher proportion of vitrinite is low in Lycospora.

To explain these anomalies one should examine the vegetational pattern of the Harbour seam as a whole as shown in Figure 4. Bands C, E and H belong to the lower part of the seam, where the abundance of Lycospora is equal to, or exceeds that of Punctatosporites. Bands I, J-1 and K belong to the upper part of the seam, where Punctatosporites is clearly the dominant genus. If Figure 5 is considered in this light, it will be seen that the Lycospora content of bands C, E and H has been reduced in relation to the bright coal adjacent to them to about the same degree, as has the Lycospora content of the upper dull bands in relation to the upper part of the seam. In the same way, the differences in the percentage of Punctatosporites in bands D and J-1, relative to its percentage in the adjacent bright coals, may be viewed.

Despite the periodic changes in the overall Punctatosporites - Lycospora pattern, which ensued during the deposition of the dull bands, this pattern returned with the renewed deposition of the bright coal. The time involved in the accumulation of these thin bands was apparently insufficient to accomplish drastic changes in the prevailing type of vegetation. An interaction between two factors appears to be indicated. One of these was of long duration and is responsible for the overall Punctatosporites - Lycospora pattern and for the general difference in petrographic composition between the upper and lower parts of the seam. This factor may be due to changes in the groundwater level as related to rate of subsidence in the basin, or to long range climatic changes. Superimposed on this general setting were relatively minor fluctuations, which produced either flooding or desiccation. These conditions were restricted in time and perhaps also in area, so that the overall vegetational patterns were not completely destroyed. They may simply have retreated to other parts of the swamp, ready to reappear as soon as the "normal" accumulation of peat once again resumed.

THE LATERAL VARIATIONS IN THE PALYNO-PETROGRAPHY OF INTERVAL 6

In Figure 6 are illustrated the results of the microlithotype and miospore analyses carried out on fourteen different samples of interval 6. Contrary to normal practice, four subtypes of duroclarite have been recognized. This was done on the basis of the contents of exinite and inertinite. Subtype 4 is the only type that contains more than 20 per cent exinite. Subtypes 1, 2 and 3 have less than this amount of exinite and contain respectively from 5 - 15, from 16 - 30 and from 31 - 50 per cent inertinite. Of each sample the spore assemblage has been determined and

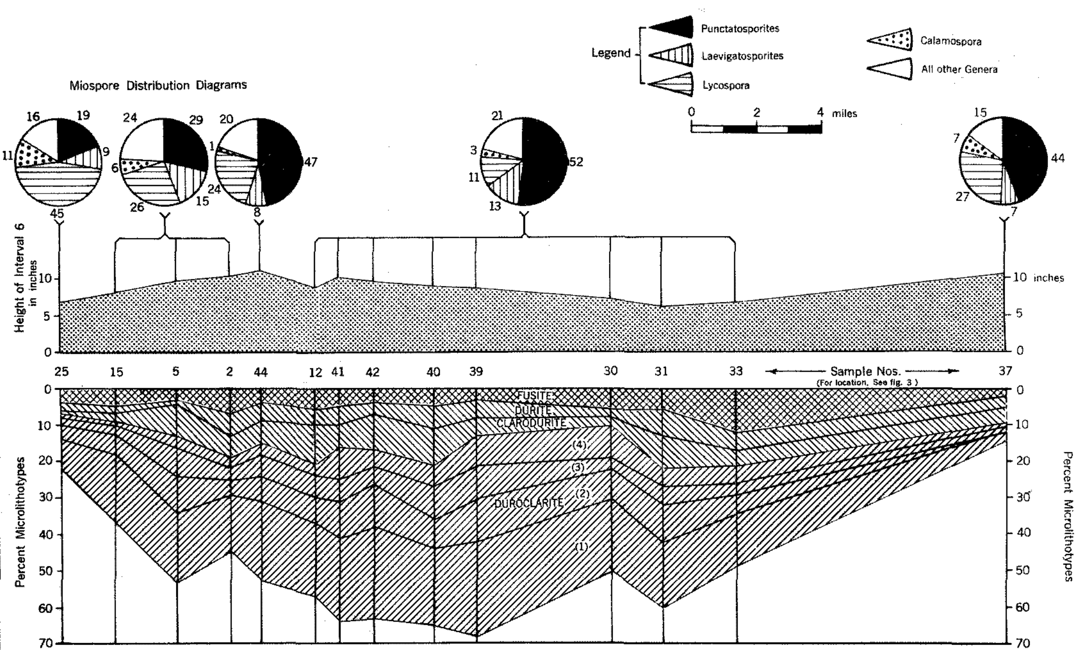

Figure 6. Lateral variations in microlithotype and miospore compositions of interval 6, Harbour Seam

is shown in Figure 6. When similar assemblages were encountered only one pie diagram, representing average values, was plotted.

In general, two main groups of spore florules can be recognized. The larger group has an average Punctatosporites content that exceeds 50 per cent. It has equal but small amounts of Lycospora and Laevigatosporites, and a negligible amount of Calamospora. All eight samples belonging to this group occur in the central part of the field (between 12 and 33), where this occurrence coincides with the highest proportions of the aggregate of duroclarite, clarodurite, durite and fusite.

In the other main group the amount of Punctatosporites has become greatly reduced, while the contents of Lycospora and Calamospora increased. This group comprises samples 2, 5 and 15, situated on the west side of the sample area, where the petrographically bright components show an increase.

The remaining three samples, numbers 37, 44 and 25, do not fit into the two main groups. Sample 37 has a relatively high Punctatosporites content, but it differs from the central main group by possessing much higher amounts of Lycospora and Calamospora. Sample 44 is similar to 37 except for its low Calamospora content. Sample 25 is the only sample analyzed in which the abundance of Lycospora greatly exceeds that of Punctatosporites. In this sample, Calamospora also reaches its highest proportions.

The microlithotype composition of the interval varies from west to east in a remarkably regular fashion. From sample 25 eastward, the aggregate of intermediate and dull microlithotypes increases from 22 per cent to a maximum of 68 per cent in sample 39, and a minimum of 14 per cent in sample 37. This significant change in the aggregate values of these components is not conspicuously developed in any one component. However, there are variations in the individual contents of duroclarite, clarodurite, durite and fusite, but they are not of great magnitude and do not follow a particular pattern.

The changes in the palyno-petrography are not haphazard. In the discussion of the megascopic aspect of interval 6 it was suggested that a mixed open moor and reed moor facies is represented. The microscopic data confirm this view, and further indicate a gradual shift towards a more open moor environment in the centre (near 39) as compared to the margin (at 25 and 37). This shift is deduced from the increase in the intermediate and dull microlithotypes and is also accompanied by a change in the vegetation, as shown by the spores. In the centre, where Punctatosporites predominates, a largely herbaceous type flora is envisaged.

At the western margin, where Lycospora greatly increased, a vegetation composed of arborescent forms was likely the dominant feature. At the eastern end, in sample 37, the picture is less clear. Here a predominantly bright coal contains an unusually high amount of Punctatosporites. However, considerable numbers of Lycospora and Calamospora are also present, thus perhaps signifying a truly heterogeneous vegetation in a mixed environment.

The palaeoecological picture presented by interval 6 shows that while the western margin of the coalfield was affected by fluvial deposition, the immediately bounding swamp consisted of a forested bog. This bog gradually changed towards the centre into a more open moor environment with a predominantly herbaceous type of vegetation. This in turn passed into the lacustrine deposits of the Glace Bay district, which in the Morien area was again bounded by a partially forested bog. As was previously mentioned, these fluvial and lacustrine deposits are, at least in part, considered to be contemporaneous with interval 6.

VARIATIONS IN ABUNDANCE OF GENUS TORISPORA OCCURRING IN ASSOCIATION WITH BAND H

Associated with band H, but occurring particularly abundant in a narrow band (3 to 6 mm wide) of clarite immediately above it, a concentration of small club-shaped spores was noted in numerous polished and thin sections. The spores are present singly or in clusters, and from a maceration study, as well as from observations reported by Horst (1957), could be identified as belonging to the genus Torispora Balme, 1952. With the exception of band H, they form a very minor component of the spore florule in all other parts of the seam.

In the map of Figure 7, the results of density counts on these spores are shown. The counts were made in polished and thin sections, and are restricted to the narrow band previously mentioned. The map indicates that the abundance of Torispora is not randomly distributed, but contours outlining areas of equal densities could be drawn.

The association of Torispora with band H is a most interesting one, in particular because Neavel and Guennel (1960) have found that these spores were likely derived from plants that grew under abnormal conditions. As was previously suggested, band H is regarded as the product of a period of desiccation, and according to Cameron (1961) the characteristics indicative of a "dry" origin become more prominent on the west side of the Sydney Mines district.

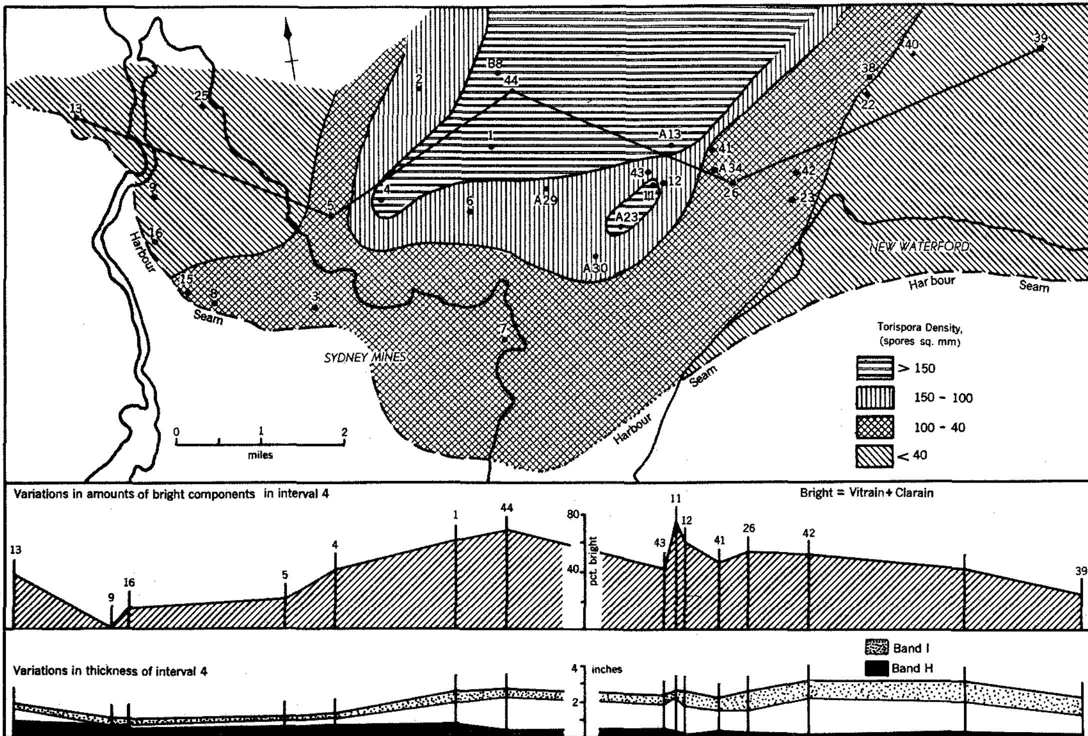

Figure 7. Variations in Torispora density above band H, Harbour Seam

In order to find a possible explanation for the density patterns illustrated in the map, the two cross-sections at the bottom of Figure 7 were prepared. The lower section shows a marked increase in the thickness of band H toward the west, which is accompanied by a reduction in the amount of bright coal between bands H and I. In sample 9, the two bands come together, signifying that at this location only the "dry" conditions of band H prevailed, with no deposition of the bright coal, which required a more moist environment. The upper section shows that an increase in the Torispora density is followed by an increase in the aggregate amount of bright lithotypes.

The most favourable area for the growth of the Torispora-bearing plants may be regarded to lie near sample 9, on account of the "dry" environment. However, this environment was poor for the preservation of plant debris, and therefore low spore densities are encountered. The high densities are present in the brighter and "wetter" centre of the map, where conditions of preservation were excellent. The distribution of the wind and water born spores is therefore related to proximity of the source (near 9) and most suitable areas of preservation (in centre). In connection with the latter it is interesting to note that sample 11 has a higher density than either 12 or 43. This sample was taken in the centre of a minor depression (or "lag") that according to Haites (1950) originated during deposition. As can be observed in Figure 7, interval 4 of sample 11 is thicker and brighter than it is on the flanks of the lag.

SUMMARY

The depositional history of a Carboniferous peat bog has been discussed by presenting data on the sedimentation, coal petrology and palynology of the Harbour seam. This seam can be traced over a distance of 30 miles, and is extensively mined along the Atlantic coast in the submarine areas of the Sydney coalfield, Nova Scotia.

The fluvial sedimentation in the limnic basin of deposition has been illustrated with a lithofacies map. In comparison with recent Mississippi deltaic plain deposits, areas with concentrations of coarse, fine and nonclastic sediments are considered respectively as the sites of ancient distributary channels, interdistributary troughs, and a subbasin of almost uninterrupted peat accumulation. The palaeotopography, caused by differential compaction of the sediments, provided a basin type depression in which peat first accumulated in the centre and then migrated outward as time proceeded. As a result equal total heights of Harbour coal in different districts of the field do not represent equal time intervals.

By arranging the megascopic petrographic information in a "facies triangle", it was possible to plot in a cross-section through the entire coalfield, the lateral changes in swamp environment of the seven intervals of the Harbour seam. This section shows two main phases of peat accumulation. The lower phase is represented by a mixed forested-reed moor and a reed moor facies. The latter reached its greatest thickness and the lowest content in ash and sulphur, near the postulated natural levee of a previously existing distributary channel. The upper phase is dominated by the partially open moor environment in the centre, and by fluvial and lacustrine deposition in the marginal areas of the coalfield.

Information on the palaeoecology of the Harbour peat bog was obtained from a microscopic palyno-petrographic study of the vertical changes in one "type" column, and the lateral variations in one time equivalent interval. The former included the seven petrographic intervals as well as the intervening dull bands. From this study it was learned that two factors affected the ecological conditions.

The major influence was of long duration and caused the separation of the seam into two distinct phases, each with its own environment of peat deposition and its associated vegetation. This vegetation, as interpreted from the Lycospora - Punctatosporites ratio, consisted during the lower phase, of a mixed flora composed of both herbaceous and arborescent forms. During the upper phase, however, a largely herbaceous type of flora predominated. The factor here involved may be a long lasting change in the level of the groundwater due to differential subsidence of the basin, or to long range climatological changes.

The other factor, of much shorter duration was superimposed on the general setting, and caused relatively minor fluctuations, which produced either flooding or desiccation. This resulted in the deposition of the dull bands, during which the prevailing type of vegetation was affected but not drastically altered.

From the lateral variations observed in the one time interval studied in detail, it was deduced that while the western margin of the coalfield was affected by fluvial deposition, the immediately bordering swamp consisted of a partially forested bog. This bog changed gradually towards the centre into a more open moor environment with a predominantly herbaceous type of vegetation. This, in turn, passed on the east side into the lacustrine deposits of the Glace Bay district, which in the Morien area was again bounded by a partially forested peat bog. A gradual increase from the sides to the centre of the aggregate amount of intermediate and dull microlithotypes, accompanied by an increase in the abundance of Punctatosporites, is regarded as evidence for the stated change in environment.

A unique concentration of the genus Torispora was observed in association with one particular dull band. The density of this concentration, obtained from polished and thin sections, varied across the field and could be contoured in a distribution map. It was suggested that the "dry" environment postulated for this dull band was very favourable for the growth of Torispora-bearing plants. The density variations of the spores were the result of differences in conditions of deposition and mode of preservation.

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